PIEZO-ELECTRIC TRANSFORMER CIRCUIT

This invention relates to a piezo-electric transformer circuit and a method of operating the circuit.

Man-made piezo-electric materials such as lead zirconate titanate (PZT) are well known. The materials are often in the form of powders which can be sintered at elevated temperatures to form polycrystalline solids which can then be machined into components operable to couple between acoustic or vibrational radiation and corresponding electrical signals. The components can include, for example, ultrasonic transducers, microactuators and piezo-electric transformers.

Piezo-electric transformers are conventionally employed in power supply circuits providing high output potentials at low currents; in this context, high potential or high voltage means in the order of 100 volts to 10 kV, and low currents means in the order of tens of microamperes to milliamperes. Compared to circuits employing electro-magnetic devices for generating such high potentials, functionally equivalent circuits employing piezo-electric transformers are capable of being lighter-weight and more compact.

A conventional piezo-electric transformer circuit can incorporate a piezo-electric transformer comprising an elongate bar of PZT material comprising primary and secondary regions. In operation, an electrical drive signal is applied by the circuit to the primary region to excite vibrations therein which are coupled to the secondary region; the vibrations generate mechanical stresses in the secondary region and thereby high voltages therein, for example in the order of 1 kV. The high voltages are rectified to provide a high-voltage unipolar output from the circuit. The conventional transformer circuit suffers a problem that its efficiency deteriorates as its output is loaded; efficiency here is defined as a ratio of power delivered to a load connected to the output relative to input power provided to the circuit.

A United States patent no. 5 777 425 discloses a piezo-electric transformer comprising a rectangular plate of piezo-electric material. The transformer includes drive and pickup electrodes connected to a pulse generator for exciting the transformer at its mechanical resonance and thereby generating a high-voltage output. Applications for the transformer are disclosed in the patent,

namely in electronic copy machines, electrostatic air cleaners and for backlighting liquid crystal displays. The transformer is described as being fabricated from a known ceramic having a composition:

(a) Pb (Fe Nb) Zr Ti O_3; or
(b) Pb (Mn Sb) Zr Ti O_3; or
(c) Pb (Mn Nb) Zr TiO_3; or
(d) Pb (Fe Sb) Zr TiO_3.

Pb, Fe, Nb, Zr, Ti and O are chemical symbols corresponding to lead, iron, niobium, zirconium, titanium and oxygen respectively. Apart from disclosing the compositions, the patent does not indicate other properties required of the ceramics, for example their required mechanical Q-factor and charge coefficient.

In a published European patent application no. EP 0 730 338 A1, there is described a piezo-electric transformer for use in a low-power high-voltage power supply. The transformer is connected to an excitation circuit for driving the transformer at its resonance, and also connected to a diode rectification circuit for generating a unipolar high-voltage output potential. The transformer is described as optionally having a multilayer construction, layers of the transformer being mutually bonded by gluing, welding, brazing or similar. Piezo-electric materials suitable for fabricating the transformer are not disclosed in the published application.

In another published European patent application no. EP 0 665 600 A1, there is described a piezo-electric transformer and an associated electronic excitation circuit suitable for driving a high voltage discharge tube for backlighting liquid crystal displays. The application refers to a proprietary ceramic type HCEPC-28 made by Hitachi Metals Ltd. as being appropriate for fabricating the transformer. Moreover, the application refers to the transformer being of multilayer construction.

In the prior art, piezo-electric materials offering a relatively high piezo-electric coefficient are selected for high-power piezo-electric transformers; such relatively high piezo-electric coefficients are associated with relatively softer piezo-electric ceramics. Moreover, it is conventional practice

to design piezo-electric transformers to have associated operating resonant frequencies in the order of several tens of kHz.

The inventors have appreciated that it is not appropriate when designing high-power high-voltage power supplies incorporating piezo-electric transformers merely to select a piezo-electric transformer ceramic material purely on the basis of achieving a highest value of charge coefficient and mechanical resonance Q-factor to obtain maximum power supply conversion efficiency. Indeed, the inventors have appreciated to optimise the energy efficiency that piezo-electric ceramic dielectric loss is an important parameter which should be reduced to a relatively low level of substantially 0.005 or less at 1 kHz even at the expense of reducing charge coefficient.

According to a first aspect of the present invention, there is provided a piezo-electric transformer circuit incorporating a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the secondary region operable to provide an output signal for use in generating an output from the circuit, and vibration exciting means for exciting the transformer into vibration at its resonant frequency to generate the output signal, characterised in that the transformer comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz frequency.

The invention provides the advantage that the piezo-electric transformer is capable of being operated more efficiently, especially when the output from the circuit is more heavily loaded.

A test frequency of 1 kHz is accepted in the art as being a standard reference frequency for measuring piezo-electric material dielectric loss and is widely quoted in prior art literature. Moreover, the dielectric loss of a piezo-electric material is defined as the tangent of an electrical loss angle observed when electrically driving the material.

A hard piezo-electric ceramic material is defined as a piezo-electric ceramic material exhibiting a hardness corresponding to a Navy type I or III ceramic. Such a hard material is to be contrasted with a soft piezo-electric material which exhibits a hardness corresponding to a Navy type II

ceramic. Further definitions mutually distinguishing Navy type I to III piezo-ceramic materials are to be found in a document United States standard MIL-STD-1376 which is herein incorporated by reference.

Conveniently, the exciting means is operable to excite vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions. Operation at the modal resonance provides the advantage that vibration amplitude and associated stress levels in the transformer are magnified by a Q-factor of the resonance, thereby improving efficiency of the transformer compared to operation off-resonance.

Advantageously, the network is operable to phase shift and amplify the output signal to generate a drive signal for exciting and thereby sustaining vibrations within the transformer. Phase shifting and amplification provide a simple form of signal processing required for sustaining vibrations within the transformer. Preferably, the output signal is phase shifted in a range of 30° to 150° in the network to generate the drive signal.

It is desirable that the transformer should be capable of being driven to provide a high voltage magnification from the primary region to the secondary region. Thus, the exciting means advantageously incorporates amplifiers arranged in a bridge configuration operable to drive the transformer. The configuration enables the drive signal to have a peak-peak amplitude corresponding to up to twice a supply potential supplied to the amplifiers.

Advantageously, the exciting means incorporates at least one inductor through which the transformer is driven at its primary region, the inductor operable to electrically resonate with a capacitor provided by the primary region at a frequency corresponding to that of the vibrations. Incorporation of the inductor provides the advantages that:

(a) the primary region is capable of being tuned to appear as a resistive load to the drive signal; and

(b) higher harmonic components present in the drive signal can be attenuated, thereby counteracting spurious excitation of higher-order vibrational modes in the transformer and hence enhancing operating efficiency.

Conveniently, one of the inductors can incorporate a ferrite core. This enables the inductor to be compact.

Conveniently, the circuit incorporates rectifying means for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in the form of a unipolar potential. Rectification provides the advantage of converting the output signal from the secondary region, namely an alternating signal, into a unipolar potential for output. Preferably, the rectifying means incorporates a rectifier diode operable to provide a conductive path for the output signal to a ground potential to assist with developing the unipolar output potential.

Advantageously, the transformer is operable to generate relatively high output potentials approaching 10 kV or more. To generate this potential, the transformer is operable to impart a greater voltage amplitude to the output signal relative to that of the drive signal.

Preferably, the transformer is operable to vibrate in a longitudinal mode of acoustic resonance. Longitudinal modes of vibration can be symmetrical modes of resonance, thereby assisting to reduce vibrational energy loss from the transformer in comparison to unsymmetrical vibrational modes. Conveniently, the transformer is of elongate form operable to vibrate longitudinally along its elongate axis.

Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

In a second aspect of the invention, there is provided a method of operating a piezo-electric transformer, the method comprising the steps of:

(a) providing the transformer incorporating mutually vibrationally coupled primary and secondary regions, the secondary region providing an output signal from the transformer, the transformer being fabricated from a hard piezo-electric material having a dielectric loss of substantially 0.005 or less at 1 kHz; and

(b) establishing a feedback network for processing the output signal to generate a drive signal and applying the drive signal to excite oscillatory vibrations in the primary region which couple to the secondary region, thereby generating the output signal in the secondary region and sustaining the vibrations in the transformer.

In a third aspect of the present invention, there is provided a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the primary region incorporating a stack of piezo-electric material elements, each element incorporating electrical connections for connecting a drive signal thereto and the secondary region incorporating electrical connections for extracting an output signal therefrom, characterised in that the piezo-electric transformer comprises a hard piezo-electric ceramic material having a dielectric loss of substantially 0.005 or less at 1 kHz. Use of the hard piezo-electric material, for example a Navy type I or III piezo-ceramic material, improves efficiency of the transformer compared to an identical transformer fabricated using a softer piezo-electrical material, for example a Navy type II piezo-ceramic material.

Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

Embodiments of the invention will now be described, by way of example only, with reference to the following diagrams in which:

Figure 1 is an illustration of a piezo-electric transformer according to the invention;

Figure 2 is a schematic of an electrical equivalent circuit to the transformer shown in Figure 1;

Figure 3 is a schematic diagram of a circuit according to the invention for operating the transformer in Figure 1; and

Figure 4 is a schematic diagram of an alternative circuit according to the invention for operating the transformer in Figure 1.

Referring now to Figure 1, there is shown a piezo-electric transformer according to the invention; the transformer is indicated by 10 and comprises a primary region indicated by 12 and a secondary region indicated by 14. The regions 12, 14 are both identical in size, namely 8 mm long (l), 6 mm wide (w) and 2 mm thick (t). Exposed faces of the regions 12, 14 are mutually parallel or orthogonal. Moreover, the regions 12, 14 are each mutually joined at an interface 16 where each region provides an abutting face of size 6 mm x 2 mm.

The secondary region 14 incorporates an end face 18 on an opposite side thereof to the interface 16. The face 18 is metallized with a vacuum-deposited or sprayed metallic film, for example a silver metallic film, to which an electrical connection S1 is made by wire bonding.

The primary region 12 comprises a stack of sixteen piezo-electric planar elements, for example an element 20, each slice having a thickness of 100 μm and an area of 8 mm x 6 mm. When assembled, the stack is 2 mm thick to match the thickness (t) of the secondary region 14. Moreover, each element is metallized on its major faces with a vacuum-deposited metallic film, for example a silver metallic film. The major faces of each element are electrically mutually isolated. The elements are electrically connected in parallel in the stack to which primary electrical connections P1, P2 are made by wire bonding to exposed major faces of an upper element 20a and a lower element 20b respectively of the primary region 12. The connections P1, P2 can alternatively be made to opposite side edges of the primary region 12 where metallic film connections on the major faces of the elements are accessible.

The elements 20 and the secondary region 14 comprise a hard PZT piezo-electric ceramic material exhibiting a dielectric loss of 0.005 or less at a test frequency of 1 kHz. The hard material has a product reference PZT26 and is manufactured by a Danish company Ferroperm A/S, Hejreskovvej 18A, DK-3490 Kvistgaard, Denmark. The hard PZT26 material is to be contrasted with softer piezo-electric materials having product references PZT27 and PZT29 from the same company. The softer PZT27 and PZT29 materials exhibit reduced resonance Q-factors and greater dissipation when vibrating compared to the hard PZT26 material; moreover, such softer PZT materials exhibit a higher dielectric loss in the order of 0.02 at 1 kHz. Here, the dielectric loss of a piezo-electric material is defined as the tangent of the electrical loss angle observed when electrically driving the material. The dielectric loss also represents the ratio of resistance to reactance of a parallel equivalent circuit of a piezo-electric transformer made from the material. The dielectric loss can be measured directly using an impedance bridge, for example at an excitation frequency of 1 kHz.

Table 1 contrasts material parameters associated with the hard PZT26 piezo-ceramic material with corresponding material parameters associated with the softer PZT27 and PZT 29 piezo-ceramic materials.

Table 1

Parameter	PZT26 (hard)	PZT27 (soft)	PZT29 (soft)
Relative dielectric constant @ 1 kHz	1300	1800	2900
Dielectric loss factor (tan δ)	0.003	0.017	0.019
Curie temperature (^{o}C)	330	350	235
Coupling factor k_{33}	0.68	0.7	0.75
Piezo-electric charge coefficient (10^{-12} C/N), $-d_{31}$	130	170	240
Density (10^3 kg/m^3)	7.70	7.70	7.45
Resonant mechanical Q_m factor	>1000	80	90

During manufacture, the elements and the secondary region 14 are poled prior to being joined together using a rigid epoxy bonding agent to fabricate the transformer 10. Poling involves

applying a momentary electric field to the region 14 and the elements of sufficient magnitude to cause a permanent electrical polarisation therein; the polarisation is reversible by heating to or above the Curie temperature in Table 1 or by applying a sufficiently powerful depolarising electric field.

When assembled for operation, the transformer 10 can be mounted onto compliant air-filled expanded plastic foam. It can alternatively be supported on point mounts which engage onto areas of the transformer 10 corresponding to vibrational nodes when the transformer 10 is vibrating; such point mounts assist to enhance resonance Q-factor of the transformer 10 when resonating at one or more of its resonant modes by reducing vibrational energy loss therefrom. The use of foam plastics provides a robust shock-resilient mount for the transformer 10, thereby assisting to counteract fracture of the transformer 10 when subjected to high g-forces, for example accelerations in excess of 10g.

Operation of the transformer 10 will now be described with reference to Figure 1. The connections P1, P2 are connected to a source (not shown in Figure 1) providing a drive signal which imposes an alternating drive potential difference between the connections P1, P2. Because the elements are polarised in a first direction parallel to an arrow 22, namely in a direction normal to major surfaces of the elements, the elements expand and contract in the first direction in response to the drive signal. This expansion and contraction of the elements in the first direction results in them exhibiting an associated lateral expansion and contraction in second and third directions indicated by arrows 24, 26 respectively. The arrows 22, 24, 26 are mutually perpendicular. On account of the primary and secondary regions 12, 14 being joined together and thereby vibrationally coupled together, the secondary region 14 vibrates in sympathy with the primary region 12. Since the secondary region 14 is polarised in a direction parallel to the arrow 26, acoustic vibrations in the secondary region 14 are capable of developing an alternating potential at the connection S1.

The transformer 10 is capable of vibrating in a number of different resonance modes depending upon the frequency of the drive signal applied, each mode corresponding to a different manner in which the transformer 10 is capable of flexing. When the frequency of the drive signal corresponds to that of a particular mode, that particular mode becomes preferentially excited. The degree to

which the mode is excited depends upon the magnitude of the drive signal and also on effectiveness of excitation of the mode from the connections P1, P2.

The transformer 10 is designed to function in a longitudinal mode of resonance at 100 kHz in which the regions 12, 14 alternately expand and contract in opposition in directions parallel to the arrow 26. This mode of operation results in there arising most motion at extremities of the regions 12, 14 remoter from the interface 16 and least motion at the interface 16; in other words, the interface 16 functions as a nodal point and exposed ends of the regions 12, 14 functional as antinodal points. When the secondary region 14 vibrates, stresses arising from periodic elongation thereof result in generation of an alternating potential at the connection S1. The transformer 10 is thereby capable of converting a relatively smaller drive potential applied to the primary region 12 between the connections P1, P2 into a corresponding relatively larger magnified potential at the connection S1. For example, a 5 volt peak-peak 100 kHz sinusoidal signal applied to the connections P1, P2 can result in generation of a 300 volt peak-peak sinusoidal signal at the connection S1. Signal magnification provided by the transformer 10 is referred as its magnification factor, N. The factor N is determined by physical dimensions of the transformer 10, namely its dimensions t and l, as well as its Q-factor associated with its longitudinal mode of resonance and also piezo-electric coupling coefficients associated with the primary and secondary regions 12, 14 respectively. Equation 1 expresses this relationship:

$$N = \frac{Q_m k_0 k_{13} k_{33} l}{t} \qquad \text{Eq. 1}$$

where

Q_m = resonant mechanical Q factor;

k_0 = proportionality coefficient;

k_{13} = primary region coupling coefficient associated with coupling of piezoelectrically induced stress arising from applying an electric field in a primary region poling direction to stress in a direction perpendicular to the poling direction;

k_{33} = secondary region coupling coefficient associated with coupling stress in the secondary region poling direction to a corresponding secondary electric field in the poling direction;

l = length of primary and secondary regions; and

t = thickness of primary and secondary regions.

Incorporation of a plurality of planar elements into the primary region 12 increases current output performance of the transformer 10 compared to a piezo-electric transformer of similar external physical dimensions and material incorporating only a single element in its primary region.

Referring now to Figure 2, there is shown an electrical equivalent circuit to the transformer 10, the circuit being indicated by 100. Components in the circuit 100 do not exist in reality but represent mechanical resonance characteristics of the primary and secondary regions 12, 14 near their 100 kHz longitudinal resonance mode.

The primary region 12 includes the connections P1, P2 which are mutually connected through a series resonant circuit comprising an inductor Lp, a capacitor Cp and a resistor Rp; the series resonant circuit is resonant at a frequency fp. Moreover, the connections P1, P2 are also mutually connected through two capacitors Cep connected in series. The capacitors Cep represent an electrical capacitance between metallisation layers incorporated onto the slices in the primary region 12 and are each in the order of several hundred nanofarads. The series resonant circuit represents mechanical resonance of the primary region 12 when vibrating in its longitudinal mode of vibration.

The secondary region 14 includes a parallel resonant circuit comprising a resistor Rs, an inductor Ls and a capacitor Cs connected in parallel with a current source Is. The parallel resonant circuit is resonant at a frequency fs. The current source Is incorporates two terminals, namely:

(a) a first terminal connected to one side of the parallel resonant circuit and also to a junction where the capacitors Cep mutually join; and

(b) a second terminal connected to another side of the parallel resonant circuit and also to the connection S1.

In operation, most power is delivered to the primary region 12 when a drive signal applied across the connections P1, P2 is a sinusoidal signal having a frequency equal to fp. When the series resonant circuit is driven at resonance, it presents a resistive load Rp across the connections P1, P2. However, the capacitors Cep appear in parallel with Rp and provide a capacitive load to the connections P1, P2; as a consequence, a primary current ip supplied to the connections P1, P2 is phase advanced relative to a potential developed across the connections P1, P2 at the frequency fp. The inventors have appreciated that determination of current-voltage phase difference when driving the primary region 12 is not an optimal manner in which to ensure that the transformer 10 is operating efficiently at resonance because it is difficult to determine precisely when the series resonant circuit is being driven at its resonant frequency fp.

In operation, the parallel resonant circuit in the secondary region 14 exhibits a slightly different resonant frequency relative to the series resonant circuit in the primary region 12; this corresponds to fp and fs being unequal, namely there arises a frequency difference Δf equal to fs-fp. This frequency difference varies depending upon load applied to the terminal S1. Thus, the inventors have appreciated that operating the primary region 12 at its resonant frequency fp does not necessarily ensure that the secondary region 14 is being operated precisely at its resonance. In consequence, it is found that efficiency of operation of the transformer 10 reduces considerably when a load is applied to the connection S1.

When resonating in its longitudinal mode at 100 kHz and unloaded, the transformer 10 exhibits a resonance Q-factor of approximately 300. When loaded at the connection S1, this Q-factor can reduce to 60 which modifies Δf. Mechanisms for acoustic energy loss from the transformer 10 which determine its Q-factor include:

(a) intrinsic losses within the PZT material arising from frictional losses at PZT particle grain boundaries therein;

(b) air damping effects;

(c) acoustic losses to a foam or point mount employed to support the transformer 10; and

(d) electrical load applied to the connection S1 which absorbs acoustic energy from the secondary region 14.

In operation, mechanism (d) is most significant at changing the Q-factor and hence Δf.

The inventors have appreciated that driving the transformer 10 closer to its optimum operating condition is a complex problem. Whereas fixed frequency primary drive is conventionally employed in piezo-electric transformer power supplies, the inventors have realised that output from the secondary connection S1 provides a most reliable signal from which to derive a drive signal for the primary region 12 which enables the transformer 10 to operate more efficiently when loaded at its secondary region 14.

Referring now to Figure 3, there is shown a schematic diagram of a circuit according to the invention for operating the transformer 10. The circuit is indicated by 200 and comprises:

(a) the piezo-electric transformer 10;
(b) a bias network indicated by 210 and included within a dotted line 220;
(c) first and second amplifiers indicated by 230, 250 and included within dotted lines 240, 260 respectively;
(d) a feedback network indicated by 270 and included within a dotted line 280; and
(e) an output network indicated by 290 and included within a dotted line 300.

The circuit 200 is connected to supply lines Vs and 0v which are operable to provide input power to the circuit 200.

The bias network 210 incorporates two 100k resistors R1, R2 connected in series, namely the resistors R1, R2 are each connected at one end thereof to the supply lines Vs, 0v respectively. The resistors R1, R2 are operable to provide a bias potential where they are mutually connected.

The amplifiers 230, 250 are identical and each incorporates an operational amplifier connected to the supply lines Vs, 0v. The operational amplifiers are arranged in inverting configuration with resistors R3, R4 defining a voltage gain provided by the first amplifier 230 and resistors R5, R6 defining a voltage gain provided by the second amplifier 250. The resistors R3, R6 are 470k

resistors and the resistors R4, R5 are 3M3 resistors. The bias network 210 is connected to the amplifiers 230, 250 and operable to provide a bias potential thereto. Outputs from the amplifiers 230, 250 are connected to connections P1, P2 of the transformer 10 respectively. The amplifier 230 incorporates an input which is connected to an output from the feedback network 270, and the amplifier 250 incorporates an input which is connected to the output from the amplifier 230.

The feedback network 270 comprises a 2M2 resistor R7 and a 10 pF capacitor C1 connected in series to the supply line 0v. The resistor R7 provides a input which is connected to the connection S1 of the transformer 10. A junction where the resistor R7 is joined to the capacitor C1 provides a output which is connected to the input of the amplifier 230 through a 100 nF coupling capacitor C3.

The output network 290 comprises two silicon rectifier diodes D1, D2 exhibiting a reverse breakdown voltage of approximately 1kV and a fast switching speed of 100 ns or less. The diode D1 is connected by its cathode to the connection S1 and its anode to the supply line 0v. Moreover, the diode D2 is connected by its anode to the connection S1 and its cathode to a secondary output S2 from the circuit 200. Furthermore, the network 290 also incorporates a 100nF output capacitor C2 connected between the output S2 and the 0v supply line. In operation, a high voltage potential of several hundred volts relative to the supply line 0v is provided at the output S2. The diode D1 is arranged to provide a discharge path to the supply line 0v to assist with developing the high potential at the output S2.

The feedback network 270 is arranged to exhibit a time constant which is at least five times longer than a cycle time period associated with the frequency fs. This ensures that a signal provided by the network 270 to the amplifier 230 is approximately in a range of 30° to 90° phase shifted relative to an output signal provided by the transformer 10 at the connection S2; the phase shift is necessary for the circuit 200 to maintain oscillation. However, the circuit 200 is capable of oscillating satisfactorily for a phase shift in a range of 30° to 150° in the network 270; extra components are required in the network 270 to obtain phase shifts in excess of 90°.

Operation of the circuit 200 will now be described with reference to Figure 3. When power is supplied through the supply lines Vs, 0v to the circuit 200, the bias network 210 provides a bias potential to the amplifiers 230, 250, the bias potential substantially intermediate between Vs and 0v. The bias potential biases the amplifiers 230, 250 to operate symmetrically with reference to the bias potential.

The amplifiers 230, 250 provide voltage gain around a feedback loop comprising the transformer 10, the feedback network 270 and the amplifiers 230, 250. The feedback loop is arranged to have greater than unity gain therearound at the frequency fs, namely at approximately 100 kHz; the feedback network 270 provides a phase shift required for sustaining oscillation around the loop. When the circuit 200 is initially energised, noise injected into the circuit 200 by the amplifiers 230, 250 becomes amplified around the feedback loop to establish a major oscillation at the frequency fs. This feedback loop provides the advantage that the circuit 200 will automatically restart in the event of its supply lines being momentarily interrupted or the transformer 10 being subjected to violent shock which disturbs its vibration.

As illustrated in Figure 2, the secondary connection S1 is capacitively coupled within the transformer 10 to the primary connections P1, P2. As a consequence, the diode D1 provides a discharge path for the connection S1 during a first half cycle and the diode D2 provides a charging path to charge the capacitor C2 during a second half cycle. The capacitor C2 thereby becomes progressively charged in operation to a high potential of several hundred volts. The high potential is a unipolar potential.

The circuit 200 incorporates an important feature that the primary connections P1, P2 are driven by a signal derived from the secondary connection S1. This feature enables the circuit 200 to adapt to changes in the secondary region 14 resonant frequency fs in response to loading applied to the output S2, thereby enhancing efficiency of the circuit 200 under load conditions.

The amplifiers 230, 250 are connected in bridge configuration. This configuration provides the advantage that the amplifiers 230, 250 are capable of driving the transformer 10 with a drive signal across its primary connections P1, P2 which has a peak-peak voltage amplitude of approximately

twice that of a potential different between the supply lines Vs, 0v. Thus, this configuration makes the circuit 200 capable of providing a high output voltage approaching several hundred volts when operating on a supply line potential difference of 5 volts.

It is important that the diodes D1, D2 are capable of switching sufficiently rapidly to counteract the diodes D1, D2 momentarily both conducting and thereby shorting the capacitor C2 to the supply line 0v; if the diodes D1, D2 switch insufficiently rapidly, operating efficiency of the circuit 200 is degraded. Small junction area silicon diodes incorporating graded doped junctions to give high inverse breakdown voltage characteristics are especially suitable for use as the diodes D1, D2.

Although the circuit 200 is arranged to excite the transformer 10 therein to vibrate in its longitudinal mode at resonance at a frequency of 100 kHz, the circuit 200 can be adapted to operate at a higher resonance mode of the transformer 10, or example at 200 kHz; to achieve operation at such a higher-order mode, the feedback network 270 can incorporate a bandpass filter adapted to preferentially transmit signals in a frequency range of the higher-order mode, thereby enabling the feedback loop to maintain oscillation in the frequency range of the higher order mode and not at lower order modes. Such higher frequency operation provides the advantage that less ripple is evident at the output S2 although the diodes D1, D2 need to be capable of switching more rapidly in order to counteract increased switching losses occurring as a consequence of operating at higher frequencies.

Referring now to Figure 4, there is shown a schematic diagram of an alternative circuit according to the invention for operating the transformer 10. The alternative circuit is indicated by 400 and is identical to the circuit 200 except that an inductor L1 is incorporated between the output of the amplifier 250 and the connection P2 of the transformer 10. The inductor L1 is arranged to exhibit an inductance which is resonant at the frequency fs with the series connected capacitors Cep shown in Figure 2.

Incorporation of the inductor L1 provides the advantages that:

(a) the primary region can be tuned so that longitudinal resonance thereof corresponds to the current ip and a drive potential applied across the connections P1, P2 being mutually in phase; and

(b) inclusion of the inductor L1 assists to prevent square-wave drive signals provided by the amplifiers 230, 250 from spuriously exciting higher-order resonance modes in the transformer 10 when attempting to drive it at its fundamental longitudinal vibrational mode. Spurious oscillation can arise when the drive signal is a square wave signal including an extensive spectrum of odd harmonics whose associated frequencies can coincide with frequencies of higher order resonant modes of the transformer 10.

The inductor L1 can be fabricated by winding enameled copper wire around a small ferrite bead to provide an inductance in the order of 30 μH to resonate at 100kHz with the capacitors Cep. Use of a ferrite bead provides a compact miniature inductor assembly. Alternatively, the inductor L1 can be fabricated as an air-cored coil; such construction is more attractive for higher power applications. Moreover, if required, the inductor L1 can comprise a plurality of smaller inductors connected together.

Experimental verification has demonstrated that inclusion of the inductor L1 improves operating efficiency of the circuit 400 compared to the circuit 200.

In a modified version of the circuit 400, an additional inductor is incorporated between the connection S1 and the networks 270, 290; inclusion of this inductor further enables fine tuning of the transformer 10 to be achieved. The additional inductor is arranged to resonate with a capacitance provided by the transformer 10 at its connection S1 at a frequency corresponding to that of a operational mechanical resonance of the transformer 10. Moreover, in a further modified version of the circuit 400, there can be incorporated the additional inductor connected to the connection S1 as described above with the inductor L1 omitted.

It will be appreciated by those skilled in the art that modifications to the transformer 10 and to the circuits 200, 400 can be made without departing from the scope of the invention. For example, the transformer 10 can incorporate in a range of 2 to 40 elements. Moreover, physical dimensions of

the transformer 10 can be modified, for example it can be made smaller to operate at a relatively higher frequency, or it can be made longer and thinner to provide it with an enhanced magnification factor N. The enhanced magnification factor is desirable when greater output potentials are to be generated.

With regard to construction of the transformer 10, its elements can be assembled by eutectic metal bonding techniques instead of employing rigid epoxy agents; such techniques provide a higher Q-factor to a transformer thereby fabricated. Moreover, the transformer 10 can be adapted to incorporate one primary region and two secondary regions bonded onto opposing side faces of the primary region, this provides the advantage that greater secondary region output currents can be thereby obtained.

Although hard PZT materials are used for fabricating the transformer 10, alternative hard man-made piezoelectric materials can be substituted if necessary, for example materials incorporating piezo-electric polyvinylidene fluoride (PVDF).

The transformer 10 and its associated circuits 200, 400 are capable of providing high potentials suitable for operating high voltage sensors, for example miniature Geiger-Muller tubes for detecting ionising radiation, as well as assisting to provide rear illumination in back-lit liquid crystal displays. Since the transformer 10 and its circuits 200, 400 are capable of being compact, they can be incorporated into personnel-wearable equipment, for example portable electronic radiation dose monitors including solid state memory for data recordal purposes.